

## EVALUATION OF STRAIN-INDUCED SURFACE CHANGES BY OPTICAL CORRELATION

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## INTRODUCTION

Previous experiments in our laboratory [1,2] have demonstrated that changes in optical correlation intensity can be used to monitor small strain applied, for example, to aluminum alloy specimens in simple tension. By analyzing data separately for specimen translation, elastic strain, and plastic strain, respectively, we inferred that irreversible changes in correlation intensity associated with plastic strains of the order of  $10^{-3}$  are caused by accompanying changes in surface topography [2]. In this paper, we present results which link metallographic observations of surface slip and related topographic changes directly to corresponding changes in optical correlation intensity, during uniaxial tensile straining of a stainless steel heat treated to two different initial conditions. The results show that in a given material, correlation intensity is not a unique function of plastic strain, but that it depends on the detailed topographic changes which occur when strain is applied.

## OPTICAL CORRELATION

We have described and analyzed the optical correlation technique and its application to nondestructive evaluation in detail elsewhere [3]. Briefly, a two-stage procedure is used. First, a hologram is made by superimposing light scattered from the surface to be interrogated on a plane-wave reference beam from the same coherent source. A thermoplastic-photoconductor device is used to record the hologram. Multiple record-erase cycles can be performed, if necessary, on the same recording plate. Second, the reference beam is blocked. Light scattered by the object surface is then transformed by the hologram into a beam with the same amplitude and phase characteristics as the original reference beam, provided no change has occurred in the position, reflectivity, or topography of the surface. The intensity of the central peak of this reconstructed reference beam, termed the correlation intensity, is measured. Changes in the topography or position of the specimen surface will cause corresponding changes in correlation intensity, for example, when strain is applied to the specimen.

## PROCEDURE

Tensile specimens were fabricated from solution-treated round bar stock of age-hardening A286 stainless steel 12.7mm in diameter. The chemical composition of this steel was (in wt. %): 24.71Ni, 14.07Cr, 2.26Ti, 1.34Mo, 0.26V, 0.18Al, 0.15Si, 0.13Mn, 0.049C, 0.012P, 0.006S, 0.005B with a balance of Fe. A flat surface 3mm wide was machined on opposite sides of the cylindrical 10mm gauge length. The machined specimens were then resolutionized for 1h at 980°C, oil quenched, and subjected to one of two heat treatments. The first group was aged 10h in air at 650°C and air cooled, producing an underaged austenitic microstructure with some inclusions, but no strengthening precipitates visible in the optical microscope. The second group was aged 100h in air at 780°C and air cooled to produce an overaged microstructure consisting of Ni<sub>3</sub>Ti type precipitates (visible in the optical microscope) in an austenitic matrix. The tensile properties of the underaged (UA) and overaged (OA) material are given in Table I, which shows that the yield strengths are essentially equal. However, UA and OA material exhibits markedly different surface topography at the same plastic strain (see results section).

After heat treatment, the specimen gauge section was ground and polished longitudinally by hand, finishing with 0.05 micron alumina abrasive prior to testing. Tensile tests were conducted at room temperature, in air, at a strain rate of approximately  $10^{-4}\text{S}^{-1}$  in total strain control using a closed-loop electrohydraulic machine (MTS system 810). Longitudinal strain was measured by means of a clip-on resistance gauge with a nominal strain resolution of  $10^{-5}$ . A hologram was recorded prior to straining the specimen, and correlation intensity,  $I_C^0$ , was measured after straining the specimen, returning it to zero load and compensating for specimen translation. A detailed description of this procedure has been given by Sigler and Haworth (1). The procedure was then repeated, the incremental plastic strains for each individual load cycle being summed to give total plastic strain  $\epsilon_p$ , as shown schematically in Fig. 1.

Finally, the surface changes occurring on companion specimens were recorded as a function of plastic strain using a metallurgical microscope equipped for Nomarski interference contrast. This technique enhances the apparent surface relief and enabled us to detect surface slip at residual plastic strains as low as  $1 \times 10^{-4}$ .

## RESULTS AND DISCUSSION

Correlation intensity is shown as a function of cumulative plastic strain for each heat treated material in Fig. 2. The data follow straight lines on a semilogarithmic plot and are described by the simple relationship

$$I_C^C = I_C^0 \exp(-B\epsilon_p) \quad (1)$$

where  $I_C^0$  is the correlation intensity prior to the application of strain, and B is a material-dependent parameter which describes the sensitivity of correlation intensity to applied plastic strain. Equation (1) is valid from zero strain at least up to 1% plastic strain where our tests were discontinued. Correlation intensity is very sensitive to applied strain, the numerical values of B per unit strain being  $2.2 \times 10^2$  for OA material and  $4.2 \times 10^2$  for UA material. Thus, the correlation intensity is reduced by almost one order of magnitude after 1% strain in OA material, and almost two order of magnitude in UA material. We have shown analytically elsewhere [2, 3] that changes in  $I_C^C$  are a measure of corresponding changes in surface topography, so that in the present case we expect the parameter B to depend on the overall topographic changes which take place on the speci-

Table I. Tensile Properties of A-286 Stainless Steel Investigated in This Study\*

	UA	OA
0.2% Offset Yield Strength**, MPa	445	450
Ultimate Tensile Strength, MPa	875	799
Uniform Elongation, %	54	37
Elongation to Fracture, %	76	56
Reduction of Area, %	61	49

\* Average of 2 tests in stroke control.

\*\* Average of 4 tests in strain control.

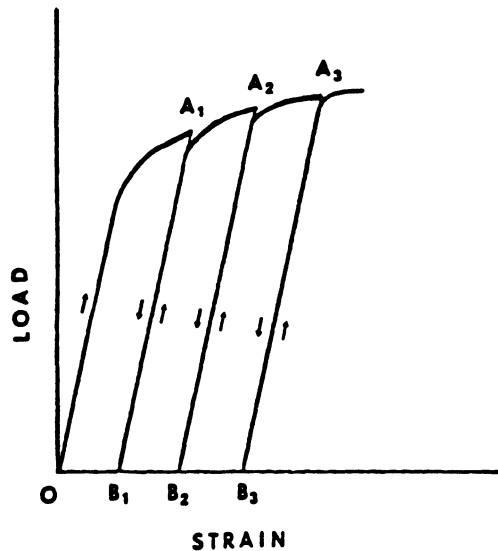


Fig. 1. Procedure for plastic strain experiments (schematic). The specimen is strained to point  $A_1$ , unloaded to  $B_1$ , and correlation intensity is then measured corresponding to plastic strain  $OB_1$ . The procedure is repeated and successive incremental strains  $B_1B_2$ ,  $B_2B_3$ , etc. are summed for total plastic strain.

men surface when strain is applied. These changes are shown in the photomicrographs in Figs. 3 and 4 for UA and OA material, respectively, over the same range of plastic strains used for the correlation experiments. The photomicrographs show that, as expected, surface roughness caused by the development of slip bands and the tilting and mutual accommodation of individual grains increases dramatically as the plastic strain is increased to a maximum of almost 1%. Even at plastic strains as low as  $5 \times 10^{-4}$ , a number of slip lines can be detected in any randomly chosen area of the polished surface of either UA or OA material using the Nomarski interference contrast technique (Figs. 3a and 4a). Without interference contrast, however, the surfaces appear featureless in the optical microscope. The corresponding losses in correlation intensity at this strain are approxi-

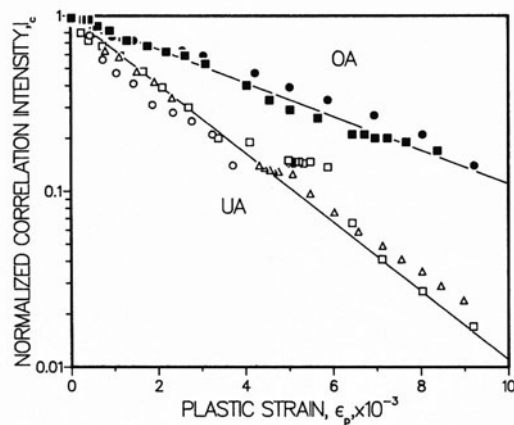


Fig. 2.  $I_c^c$  measured at zero load, as a function of total plastic strain for the analysis of  $I_c^c$  sensitivity to plastic strain (see Eq. 1).

mately 10% (OA material) and 25% (UA) of the initial (unstrained) values. Since changes in  $I_c^c$  of the order of 2% can be detected reliably, we conclude that the correlation technique is capable of detecting changes in surface topography caused by incremental strains of the order of  $1 \times 10^{-4}$ .

A second conclusion to be drawn from Figs. 3 and 4 is that the topographic changes caused by strain differ significantly in the UA and OA materials, respectively, in a manner that is consistent with the correlation intensity data. The difference in surface appearance is shown more clearly at higher magnification, as in Fig. 5 after a plastic strain of almost 1%. UA material (Fig. 5a) exhibits relatively coarse, planar slip, characteristic of a deformation mechanism in which dislocations shear through small coherent second-phase particles in materials aged to less than peak strength. The particles are not sufficiently strong to force dislocations to cross-slip frequently, so slip is distributed heterogeneously. OA material, on the other hand (Fig. 5b), exhibits extremely fine, wavy slip close to the limit of optical resolution, interspersed with occasional patches of coarser slip as shown in Fig. 4. This is consistent with the dominant deformation mechanisms being the looping of dislocations around relatively strong, incoherent second-phase particles to form Orowan loops, coupled with cross-slip to bypass the particles: the resulting slip distribution is relatively homogeneous. Although a formal analysis of reference beam reconstruction from slipped surface is beyond the scope of this paper, these observations of surface topography are entirely consistent with the relatively rapid changes in  $I_c^c$  with increasing strain seen in Fig. 2 for UA material, compared with the reduced strain-sensitivity in OA. Relative changes in the position of points on the specimen surface in the direction normal to the surface plane change the phase of the scattered beam and hence reduce the correlation intensity [3]. Relative position shifts of the order of wavelength of light will cause point-to-point correlation loss. We infer that the coarse slip

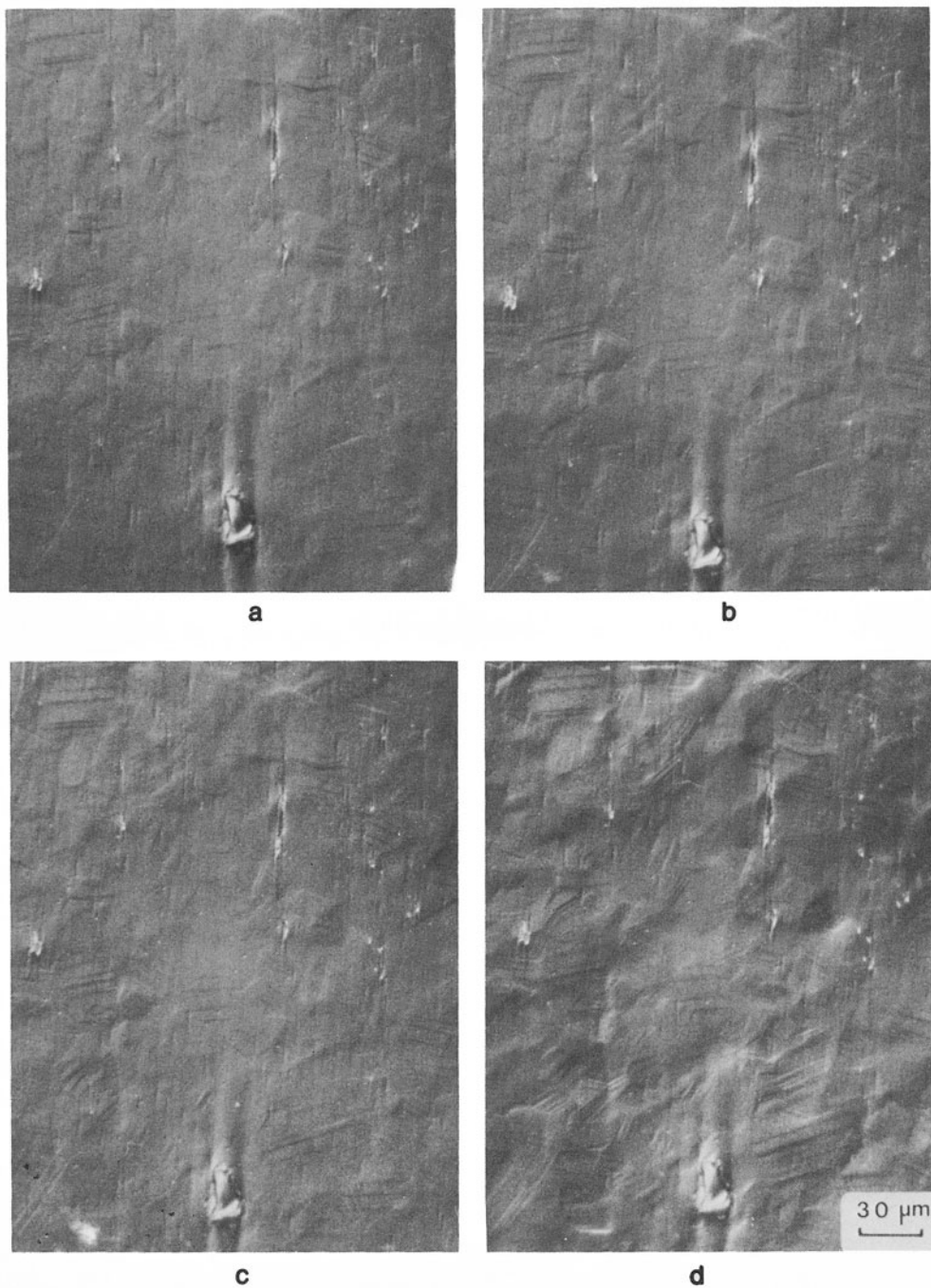


Fig. 3. Surface changes induced by plastic strain of (a)  $5.3 \times 10^{-4}$  (b)  $1.0 \times 10^{-3}$  (c)  $3.1 \times 10^{-3}$  (d)  $9.3 \times 10^{-3}$  for UA material. Nomarski interference contrast.

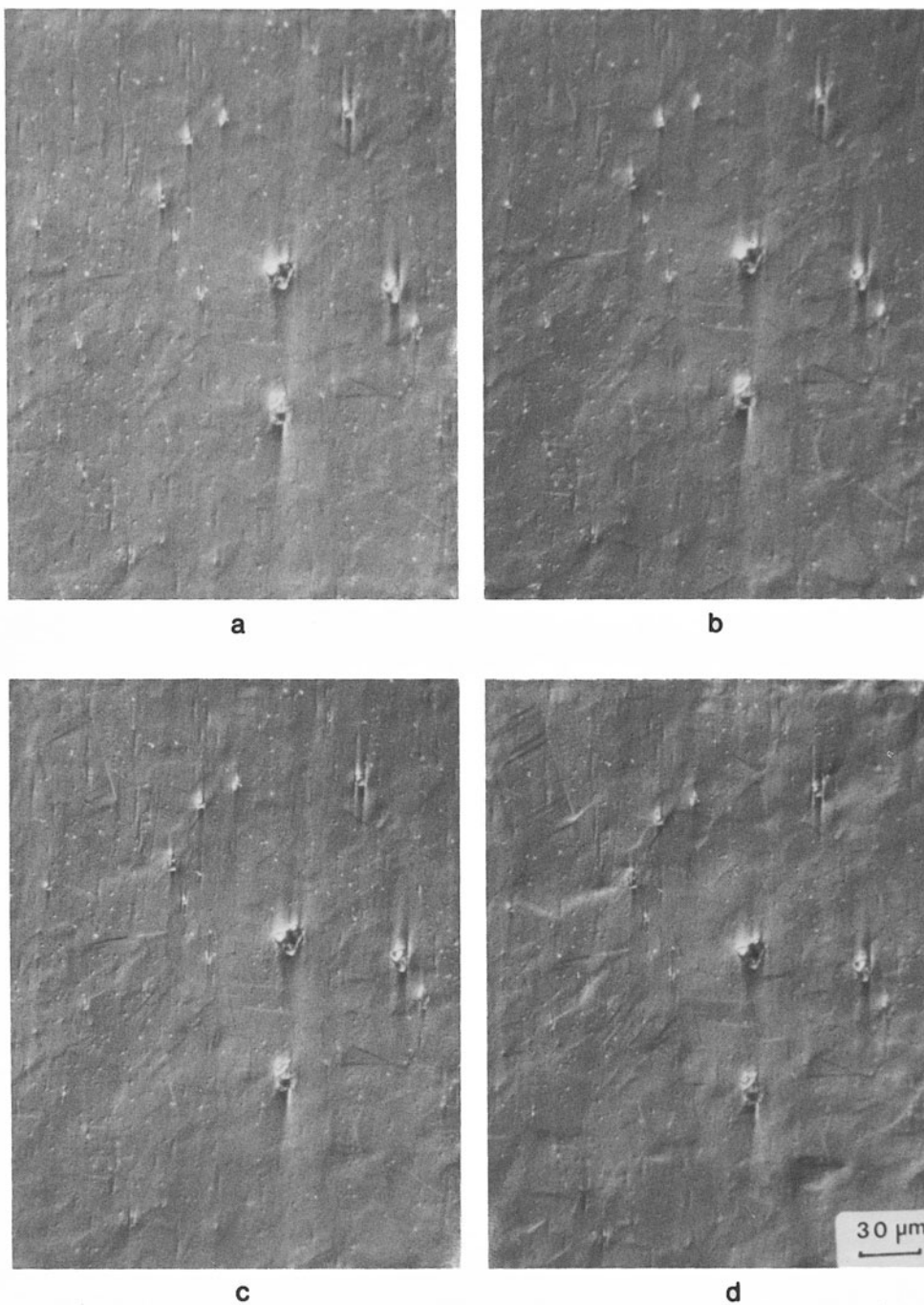


Fig. 4. Surface changes induced by plastic strain of (a)  $5.5 \times 10^{-4}$  (b)  $1.1 \times 10^{-3}$  (c)  $3.1 \times 10^{-3}$  (d)  $9.3 \times 10^{-3}$  for OA material. Nomarski interference contrast.

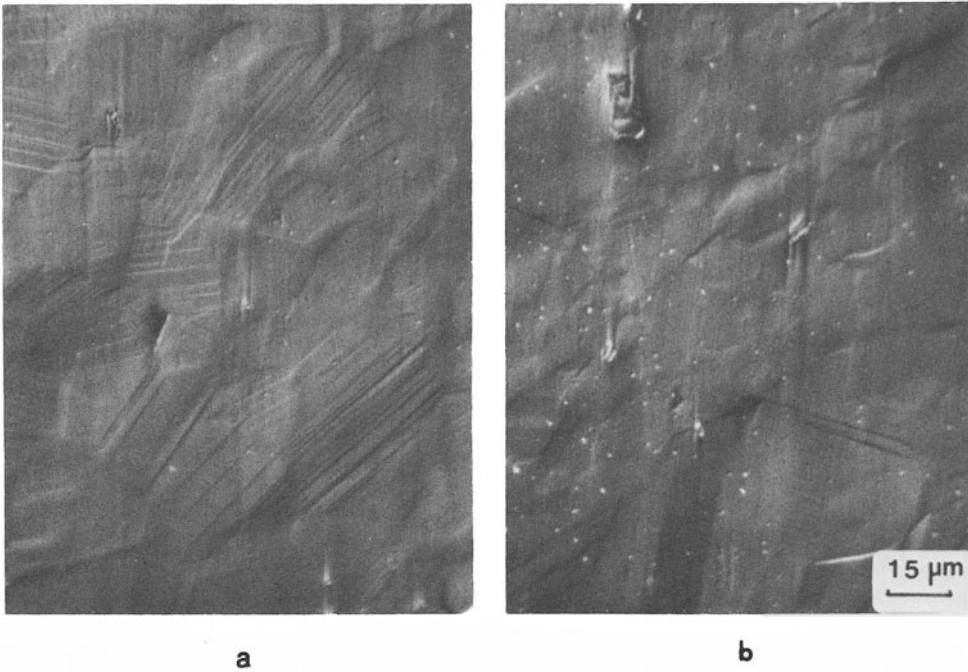


Fig. 5. Surface slip character after  $9.3 \times 10$  tensile plastic strain for (a) UA and (b) OA materials. UA material exhibits relatively coarse, planar slip, while OA material shows extremely fine, wavy slip. Nomarski interference contrast.

steps observed in UA material are highly effective in reducing the correlation intensity rapidly as plastic strain is increased. In OA material, fine slip may contribute to the observed correlation loss together with the relative tilting of grains shown in Fig. 5.

#### SUMMARY

The optical correlation intensity ( $I_c^C$ ) is an irreversible function of plastic strain obeying the relationship  $I_c^C = I_c^O \exp(-B\epsilon_p)$ , where  $I_c^O$  is the correlation intensity prior to the application of strain, and  $B$  is a parameter whose numerical value ( $4.2 \times 10^2$  for UA material,  $2.2 \times 10^2$  for OA material) depends on the slip character of the material.

$I_c^C$  changes in UA are more sensitive by an order of magnitude at  $\epsilon_p \sim 1 \times 10^{-2}$  than in OA.

The correlation technique is capable of detecting surface topography changes caused by incremental strains of the order of  $1 \times 10^{-4}$ .

Different sensitivity of  $I_c^C$  and  $\epsilon_p$  in UA and OA materials is a result of the different topographic changes caused by strains in two cases. Coarse slip steps in UA are more effective in reducing  $I_c^C$  rapidly, compared to fine slip in OA material.

## REFERENCES

1. D. Sigler and W. L. Haworth, J. NDE 2, 125 (1981).
2. M. C. Montpetit, D. Sigler, and W. L. Haworth, An Optical Correlation Technique for Deformation Testing, in: "Novel Techniques in Metal Deformation Testing," R. H. Wagoner, ed., TMS-AIME, Warrendale, PA (1983).
3. D. Sigler and W. L. Haworth, Early Detection of Metal Fatigue by Optical Correlation, in: "Non-Destructive Evaluation: Microstructural Characterization and Reliability Strategies," TMS-AIME, Warrendale, PA (1980).